

Analysis of Zero Flux Plane Behavior under Periodical Water Supply

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Abstract

Zero Flux plane (ZFP) is defined as a plane, which separates two zones of upward and downward movement of water in soil with upward and downward flow occurring simultaneously. In this study, the analysis of the ZFP movements was carried out by two sets of laboratory experiments and numerical simulations, especially paying attention to the effect of the periodical water supply. In the first set of experiment and simulation, surface Andisol soil was used and water was supplied only one time. Evaporation rate was set to 0.15 cm/day, and water was drained from the bottom of the column. The total potential profile and the ZFP movement of experiment and simulation agreed reasonably well. In the second set of experiment and simulation, subsurface Andisol was used and water was supplied periodically. In both experiment and simulation, ZFP appeared at soil surface every time water was supplied, and it gradually moved downward until it reached to the depth of 30 cm, when the ZFP disappeared. We discussed that such disappearance of the ZFP is observed when the initial soil water content at the deep zone is relatively high. In contrast, when the initial soil water content at the deep zone is relatively low, as reported in previous studies, ZFP continues to move downward for a relatively long period. Simulation of ZFP movement was also conducted for different types of soils. Based on the results of this study, a strategy for the periodical water supply in arid and semiarid regions using this ZFP concept was proposed.

Keywords: *periodical water supply, zero flux plane, unsaturated soil, Hydrus-2D, vadose zone*

1. INTRODUCTION

1.1 Background

The old term used for Zero Flux Plane (ZFP) was static zone. It was first mentioned by Richards (1954), where he used a new instrument, multiple unit tensiometer, to measure the hydraulic head and the hydraulic gradient of water in unsaturated field. In the dry periods, when evapotranspiration exceeds rainfall, the soil water in the upper part of the soil profile moves upwards towards the soil surface. At the lower depth, soil water moves downwards towards the water table due to gravity. Above the ZFP, any reduction in the soil moisture content must be due to the moisture loss caused by an excess of evaporation and evapotranspiration, whereas below the ZFP, and assuming no uptake of moisture content by roots at these depths, reduction in moisture content must be due to drainage out of the soil, i.e. recharge to the ground water table.

As Khalil et al. (2003) reviewed, most of authors have used the ZFP method either to estimate the evaporation

(Van Bavel et al., 1968), to calculate the drainage (Stone et al., 1973), or to differentiate between the drainage and the evaporation (Roman et al., 1999). Payne et al. (1990); Kanamori (1995); Diez et al. (2000) and others, all suggested the usefulness of the ZFP method to estimate the short term evaporation. On the other hand, Kirsch (1993); Roman et al. (1999) and others, all obtained reasonable estimations of long-term evaporation by using the ZFP method. For many dry climates, ground water is a major source of water supply for irrigation, industrial, and domestic demands. Ground water recharge can be estimated by the ZFP method. The reason for that is, below the maximum depth reached by the ZFP, soil water flow is always downward; hence, the water draining through any depth below this will appear eventually as recharge at the water table (e.g. Cooper, 1979; Sharma, 1985; Simmers, 1987; Bouwer, 1989). The ZFP method is considered as one of the most direct method for determining the recharge rate of ground water. Therefore, several authors have used it to estimate the ground water recharge (Hosty and Mulqueen, 1996; Abdallah et al., 2001; Tsujimura et al.,

2001 and others).

1.2 ZFP Definition

The ZFP is defined as a plane, which separates two zones of upward and downward movement of water in soil with evaporation and drainage occurring simultaneously. Water flows upward above this plane, and downward below it, i.e., the point where water is neither flowing up nor down is called the ZFP as exemplified in Fig.1 (Khalil et al 2003). With negligible lateral soil heterogeneity, the "zero flux" boundary may be assumed to be a planar. As the soil dries the plane of "zero flux" moves downward (Arya et al., 1975). Stammers et al. (1973) described the approximation of a mathematical derivation of the correct expression of ZFP depth. According to them, both evaporation and drainage can be calculated above and below ZFP as follows;

$$E = R + \int_0^{z_0(t_1)} \theta(t_1) dz - \int_0^{z_0(t_2)} \theta(t_2) dz + \frac{1}{2} \int_{z_0(t_1)}^{z_0(t_2)} [\theta(t_1) + \theta(t_2)] dz \quad (1)$$

$$D = \int_{z_0(t_1)}^Z \theta(t_1) dz - \int_{z_0(t_2)}^Z \theta(t_2) dz - \frac{1}{2} \int_{z_0(t_1)}^{z_0(t_2)} [\theta(t_1) + \theta(t_2)] dz \quad (2)$$

where:

E is evaporation over the period t_1 to t_2

R is rainfall over the same period

t is time

z is depth measured positively downwards

Z is the depth at which drainage is calculated

D is drainage over the period t_1 to t_2 through depth Z

θ is volumetric water content

$z_0(t)$ is the ZFP depth at time t .

1.3 Objective of the Study

The purpose of this paper is to study and analyze the effect of periodical water supply on ZFP movements. To achieve that, the ZFP movement experiment with only one time water supply was done for 2 days to detect and monitor ZFP movement and the experiment was compared with numerical simulation. Then periodical water supply experiment was conducted for 18 days to detect and study the effect of periodical water supply on ZFP movement, and the results were also compared with numerical simulations.

2. MATERIALS AND METHODS

Two sets of laboratory experiments and numerical simulations were performed to detect and analyze ZFP movement under different conditions of water supply. The first experiment was performed for 2 days to detect and monitor ZFP movement under only one time water supply. The second experiment was carried out to study and analyze the effect of periodical water supply on the movement of ZFP. The position of zero flux plane

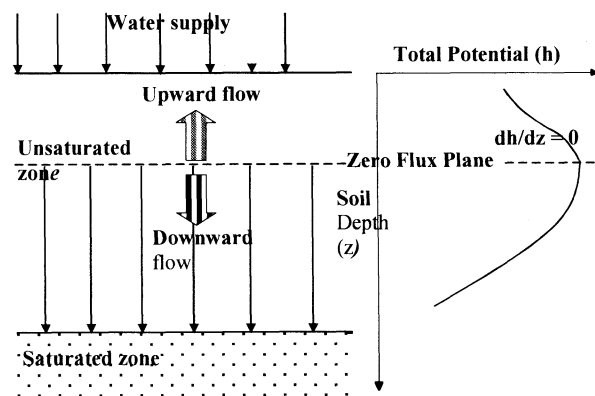


Fig.1 Zero Flux Plane Concept (Khalil et al., 2003)

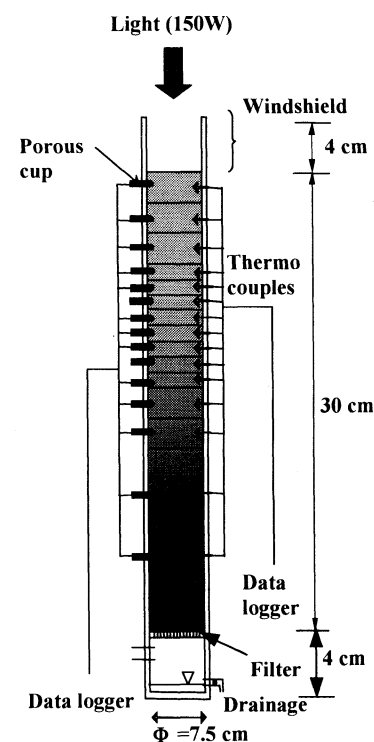


Fig. 2 The layout of ZFP movement with one water supply experiment

depth is determined at dh/dz equals to zero.

2.1 ZFP Movement with One Time Water Supply

2.1.1 Experimental set up

Fig. 2 shows the layout of the ZFP movement with one time water supply experiment. A column of 30 cm height and 7.5 cm diameter was made with acrylic rings of 2 cm height (11 sets) and 1 cm height (8 sets). The surface Andisol soil was packed in this column from bottom to top on layers by hand with a constant bulk density of 0.63 Mg m^{-3} . Electric light, 150 watts placed 20 cm above the soil surface, was supplied as a thermal source, to accelerate evaporation. Acrylic filter was provided to the bottom of the soil column. Drainage tube was supplied to the bottom as well to drain soil water. Before connecting to the

columns, transducers were calibrated. Total potential and temperature were measured by transducers and thermo couples every 5 minutes, respectively. The transducers were connected to a data logger device, CR10X that was linked to computer software. A container with a plastic sheet cover above sensitive balance was placed under the column to measure the drainage water weight periodically.

2.1.2 Boundary and initial conditions

The bottom of the column was exposed to the drainage whereas the top end was exposed to the atmospheric pressure. The column weight was measured at the beginning of the experiment. The drained water weight and column weight were measured on regular intervals through the experiment. The evaporation rate was determined from the difference between the two weights. The potential evaporation rate measured was about 0.15 cm/day which corresponds to evaporation rate in some semi arid areas. The bulk density was 0.63 Mg m^{-3} . The volumetric water content was 0.8. The column was initially wetted by providing one pore volume of water to the top of the soil just before starting the experiment.

2.1.3 Simulations

A finite element analysis software for water flow in porous media, HYDRUS-2D, was used to measure and detect ZFP numerically. Soil water retention function of van Genuchten (1980) was used in the HYDRUS-2D;

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + |\alpha h|^n\right]^m} \quad (3)$$

$$K(h) = \frac{\left\{1 - (\alpha h)^{n-1} \left[1 + (\alpha h)^n\right]^{-m}\right\}^2}{\left[1 + (\alpha h)^n\right]^{\frac{m}{2}}} \quad (4)$$

in which $m = 1 - 1/n$ and θ_r and θ_s denote the residual and saturated soil water contents, respectively, and n , α and m are parameters in soil water retention function. The ZFP detection experiment with one time water supply was simulated by one-dimensional flow in a column of 30 cm height. The column was provided with a seepage face at the bottom and an atmospheric face at the top. In the HYDRUS program, the seepage face boundary condition means that the pressure head is always uniformly equal to zero along the saturated part of the boundary, and that the outflow flux is equal to zero on the unsaturated part of the boundary. The atmospheric boundary condition is equal to the specified flux (Neumann type) boundary condition where the maximum potential rate of infiltration or evaporation is specified. In addition, maximum and minimum allowed pressures are specified and when the pressure head reaches those values, the specified pressured head (Dirichlet type) boundary condition is used so that the pressure head does not go out of the range.

$$h_A \leq h \leq h_S \quad (5)$$

where h is the pressure head at the soil surface, and h_A and h_S are, respectively, minimum and maximum pressure head allowed under the prevailing soil conditions. The value of h_A is determined from the equilibrium condition

Table 1 The values of soil water parameters of surface and subsurface Andisol.

Case	Soil Type	θ_r	θ_s	n	α	K_s (cm/min)
One water supply.	Surface Andisol	0.45	0.75	2.3	0.1	0.06
Periodical water supply	Subsurface Andisol	0.62	0.71	6.6	0.04	0.12

between soil water and atmosphere water vapor, whereas h_S is usually set to zero.

The values of the soil water parameters of the surface Andisol soil used in simulation are shown in **Table 1**. The saturated hydraulic conductivity, K_s , was determined by a falling head method and other parameters were determined by soil water retention function measured by the hanging water column method for up to 150 cm suction. The water retention curve of the drying process was used in the calculation of **Table 1**. In **Table 1**, the residual water content appears to be too high, as 0.45 for Surface Andisol and 0.62 for Subsurface Andisol. This is because the values were obtained by fitting to soil water retention function for a rather small range of suction, up to 150 cm. We treat the parameters in **Table 1** as just fitting parameters. In this simulation, we used the hydraulic parameters of drying process and did not examine hysteresis because our experiments were under drying process most of the time whereas the wetting process lasted for only a short time. In addition, the effect of hysteresis for Andisol is much smaller than for typical sandy soils (Hasegawa et al., 1994). The mathematical description of Richards' equation could be written as follows:

$$C_w(h) \frac{\partial h}{\partial t} = \frac{\partial}{\partial z} \left[K(h) \left(\frac{\partial h}{\partial z} + 1 \right) \right] \quad (6)$$

$$C_w(h) = \frac{d\theta}{dh} \quad (7)$$

where $C_w(h)$ is called the water capacity function. As boundary condition, the potential evaporation rate was set to 0.15 cm/day at the top and seepage face at the bottom. The initial conditions were set similar to those in experiments.

2.2 ZFP Movement with Periodical Water Supply

2.2.1 Experimental set up

After detecting ZFP movement by experiments and simulation, the study of the periodical water supply experiment was done to investigate and analyze the effect of the periodical water supply on the movement of ZFP. A column with 20 acrylic rings of 4 cm height and 7.5 cm in the inner diameter for each was erected. The total height of the soil column was 80 cm. The subsurface Andisol was used for this experiment. The packing of soil was done

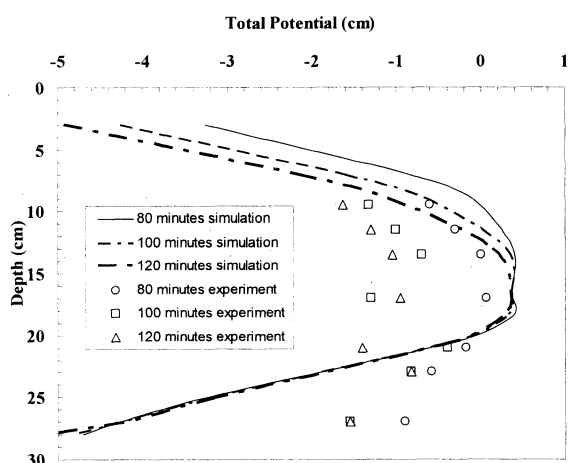


Fig. 3 Experimental and numerical ZFP movement where gravity potential is zero at soil surface

uniformly on layers. The bulk density measured before packing was 0.43 Mg m^{-3} . A container with a plastic sheet cover above sensitive balance was placed under each column to measure the drainage water weight periodically.

2.2.2 Boundary and initial conditions

The bottom of the column was exposed to the drainage whereas the atmospheric pressure was provided to the top end of the column. The bulk density of the subsurface Andisol was 0.43 Mg m^{-3} . The volumetric water content was 1.25. Periodical water supply experiment was done for 18 days. 10 mm of water was provided 5 times periodically (1st, 5th, 8th, 12th, 15th day) to the top of the column.

2.2.3 Simulations

Hydrus-2D was used to identify and measure the effect of periodical water supply on ZFP movement. The ZFP experiment was simulated by one-dimensional flow in a column of 80cm height. The column was provided with seepage face to the bottom and atmospheric face to the top. The values of soil water parameters of the subsurface Andisol used in this simulation were shown in Table 1.

3. RESULTS AND DISCUSSION

3.1 ZFP Movement with One Time Water Supply

Total potential profiles obtained by the numerical analysis were compared with those obtained by the ZFP detection experiment. Fig. 3 shows the experimental and numerical potential profiles at 80, 100, and 120 minutes obtained from the ZFP detection experiment. Except for the surface layer, the experimental and simulated results give a reasonable agreement. We could not show the agreement between experiment and simulation in the top 9 cm layer because the surface 9 cm layer was not measured due to high temperature created by the light source. This high temperature deteriorated the surface transducer. Therefore we postulate that the difference in temperature between simulation and experiment led to different ZFP movement rate where experimental ZFP movement rate is

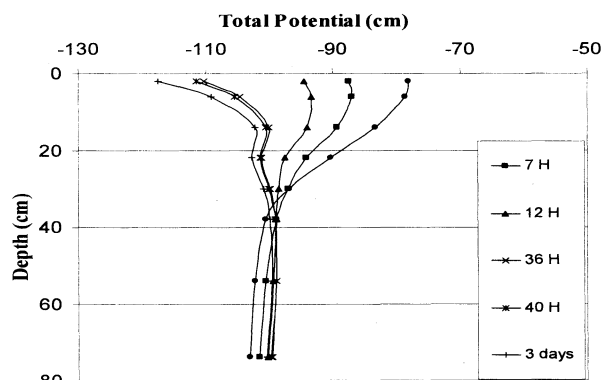


Fig.4 ZFP Movement of the first cycle of periodical supply experiment.

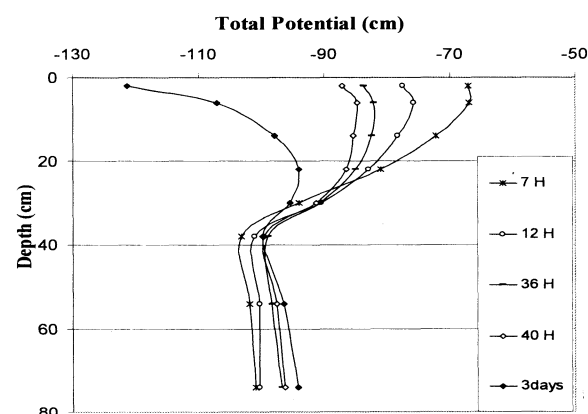


Fig. 5 Simulated ZFP movement of the first cycle of periodical water supply

slower than simulated one, but this idea has not been verified yet. For the first time ZFP movement was detected and monitored experimentally and numerically.

3.2 ZFP Movement with Periodical Water Supply

In this section, the experimental and the simulated results of the periodical water supply case are compared. Fig. 4 is the experimental total potential profiles during the first cycle, 3 days, where we can observe downward movement of the ZFP easily. There were two ZFP at each time (upper and lower) as a result of different water content between upper and lower soil, and we focus on the upper ZFP. Two main sections could be seen, first section is from the surface level up to about 40 cm depth where we observe rapid movement of the total potential profiles due to evaporation and the second section where the total potential profiles have slight movement due to near saturation phase. Fig. 5 demonstrates the simulated results of the same cycle. In this figure also, the ZFP moved downward. The total potential profiles and the ZFP movement in both Fig. 4 and Fig. 5 agreed reasonably well. However the rate of the downward movement of the ZFP in Fig. 4 and Fig. 5 was somewhat different.

In order to determine the ZFP from the measured discrete values of the total potential, it is convenient to

have a uniform expression of fitting curve for the total potential profile. From our experimental data, we made an empirical equation for the total potential profile as a function of depth as:

$$H = \ln(az + b) \exp(-cz + d) + e \quad (8)$$

where H is the total potential, a , b , c , d and e are fitting parameters. The derivative of the total potential dH/dz can be calculated as:

$$\frac{dH}{dz} = \left\{ \frac{a}{az + b} - c \ln(az + b) \right\} \exp(-cz + d) \quad (9)$$

At the depth of ZFP, $z = z_0$, $dH/dz = 0$, and therefore

$$\frac{a}{az_0 + b} - c \ln(az_0 + b) = 0 \quad (10)$$

Fig. 6 illustrates the ZFP movement determined by this method during the whole experiment period (18 days). We can observe that the experimental ZFP movement rate is slower than the simulated ZFP movement rate. The experimental ZFP reached 30 cm depth after almost 3 days while the simulated ZFP reached same depth after almost 1 day. The maximum ZFP depth, obtained from the simulated and the experimental results, is 30 cm. ZFP disappeared at 30 cm depth. The disappearance of ZFP will be discussed in the next section.

Fig. 7 represents the effect of the third cycle water supply on the ZFP movement. This cycle lasted for 5 days. We can observe easily that the ZFP, represented by the arrows, is getting deeper until 2 days. After 2.5 days, all soil water moved upward as ZFP disappeared.

3.3 Disappearance of ZFP

To understand and analyze disappearance of ZFP, a schematic diagram of the zero flux plane progress and disappearance is shown in **Fig. 8**. We can notice two stages for each cycle of water supply that explain the zero flux plane movement. At the first stage, as soon as water was provided and just after the stop of infiltration, the ZFP appeared at the soil surface. After that, the ZFP moved downward. At this stage water moved upward and downward.

In the second stage, the ZFP disappeared at 30 cm depth. The total head gradient at this phase shows that all soil water moved upward after the disappearing of the zero flux plane. When the second water supply cycle started by adding water to the soil surface and just after the stop of the infiltration, the ZFP appeared again near the soil surface and gradually got deeper as a function of time. The upper zone, near the soil surface, is relatively dry compared with the wet lower zone, below 40 cm depth.

Why did the ZFP disappear? The answer could be mainly due to water content in the deep zone. The deep zone is defined as the zone where the potential does not fluctuate, ex., the zone below 50 cm in **Fig. 7**. In general, we have two patterns of total potential profiles; one case is when deep zone is wet and water is supplied from the

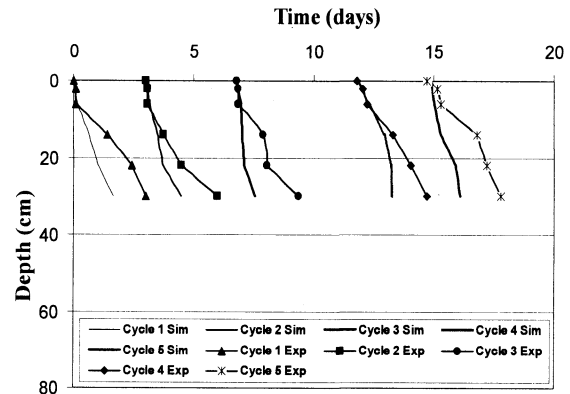


Fig. 6 ZFP Movement during the whole experiment period (18 days)

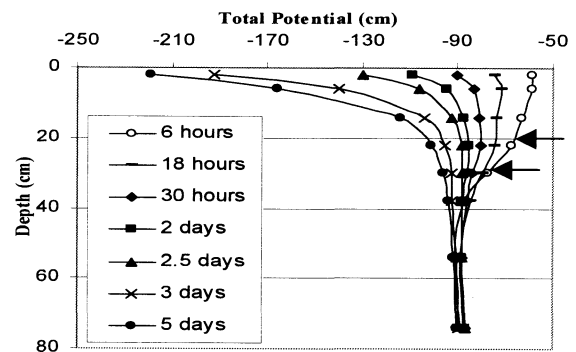


Fig. 7 Experimental ZFP progress through soil creating two stages of upward and downward flow; and upward flow only.

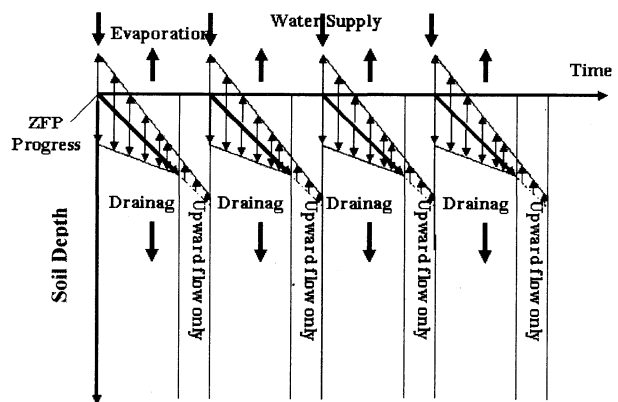


Fig. 8 Schematic diagram of ZFP progress and disappearance.

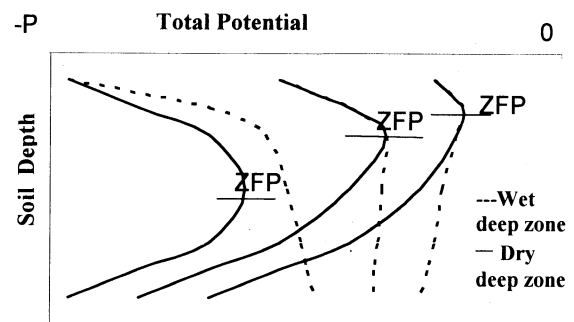


Fig. 9 Conceptual illustration of ZFP movement with different water content at deep zone

Table 2 The values of soil water parameters used in simulation

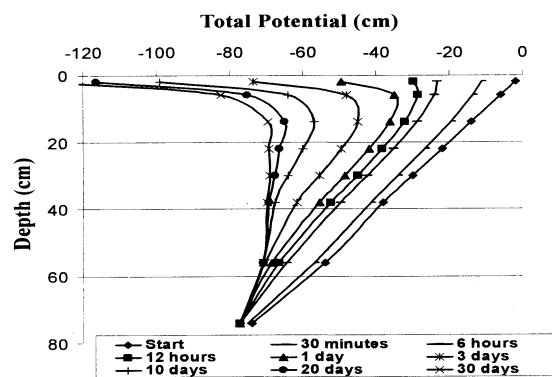
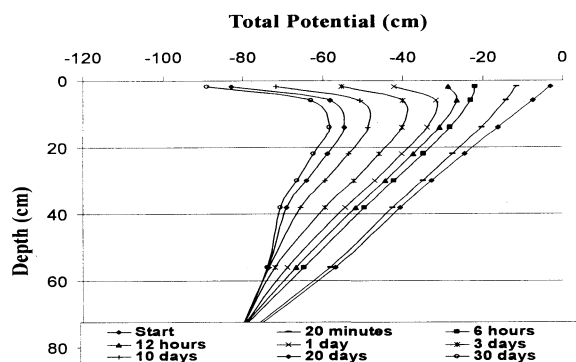
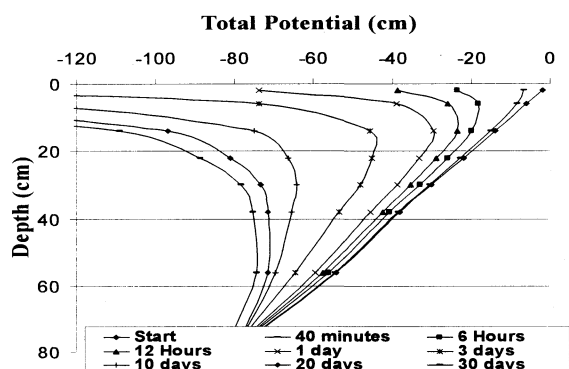
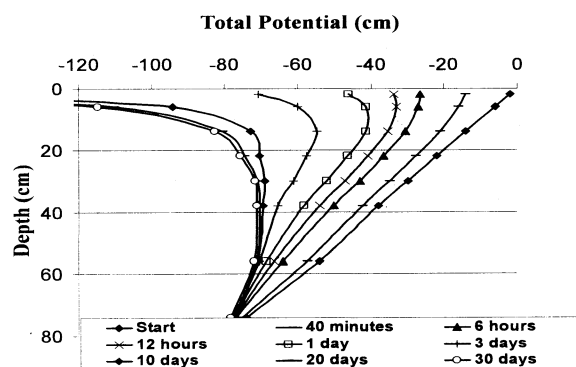
Soil Type	θ_r	θ_s	n	α	K_s (cm/min)
Loamy sand soil	0.057	0.41	2.28	0.0124	350.2
Sandy soil	0.045	0.43	2.68	0.145	712.8
Sandy clay soil	0.10	0.38	1.23	0.027	2.88
Sandy loam	0.065	0.41	1.89	0.075	106.1

surface as shown in Fig.7. Deep zone is varying from about half meter to few meters below the soil surface. In that case the wet deep zone led to the disappearance of ZFP. The other case is when the deep zone is dry and water is also supplied from the surface. In that case, the ZFP continues to move downward for a relatively long period (Wellings, 1984; Cooper et al., 1990; Sharma et al., 1991; Hosty and Mulqueen, 1996; Abdallah et al., 2001). Fig.9 illustrates the effect of the deep zone water content on the ZFP. The figure represents a relation between the total potential and the soil depth. The dashed lines exemplify a case when the deep zone is wet, and the solid lines exemplify a case when the deep zone is dry. In the former case, the ZFP moves downward and disappears, while in the latter case, the ZFP continues to move downward.

3.4 Application of Hydrus-2D to Detected ZFP Progress in Different Soils

Although the zero flux plane gradually moves downward, universal relationship for the ZFP movement with time applicable to all type of soil has not been obtained yet. To see how soil type affect the ZFP movement, the ZFP movement for four types of soils, loamy sand soil, sandy soil, sandy clay soil and sandy loam soil was simulated by Hydrus-2D. Water flow in a column of 80 cm height was modeled. The column was provided with the seepage face to the bottom and the atmospheric face to the top. 10 mm of water was provided one time only to the top of the columns for each soil at the beginning of each simulation. A simulation was carried out for a period of 30 days for all soils. The values of soil water parameters of loamy sand soil, sandy soil, sandy clay soil and sandy loam soil used in these simulations were shown in Table 2. Evaporation rate was set from 0.5 to 0.12 cm/day for both simulations.

The locations of ZFP as a function of time for loamy sand soil, sandy soil, sandy clay soil and sandy loam soil are given in Figs. 10, 11, 12 and 13. The ZFP progress was different from one soil to another. The maximum zero flux plane depth was 50 cm in 30 days for sandy clay soil (Fig.12) whereas the minimum zero flux plane position was 11cm in 30 days for sandy soil (Fig.11). For the same period sandy loam soil and loamy sand soil reached 38cm and 19cm respectively.

**Fig. 10** Simulated total potential profiles and ZFP movement prediction through loamy sand soil.**Fig. 11** Simulated total potential profiles and ZFP movement prediction through sandy soil.**Fig. 12** Simulated total potential profiles and ZFP movement prediction through sandy clay soil.**Fig. 13** Simulated total potential profiles and ZFP movement prediction through sandy loam soil.

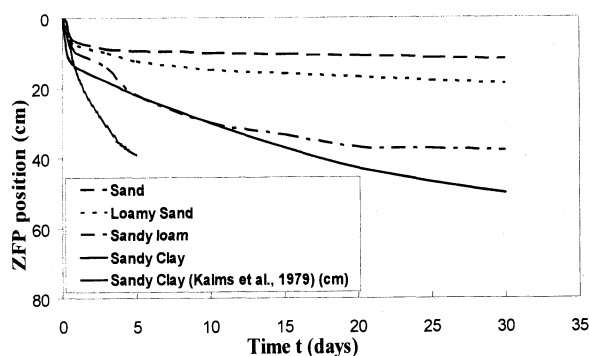


Fig. 14 The experimental and simulated progress of the ZFP position

The progress of the zero flux plane position with time in Figs. 10-13 is summarized in Fig. 14. The experimental values of the ZFP movement of sandy clay soil carried out by Kalms et al., (1979) is also shown in Fig. 14 for comparison. The rate of the downward movement of ZFP for sandy clay soil is 8 cm/day for field experiment of Kalms et al. (1979) and 2.4 cm/day for our simulation. This difference may have been caused by the difference of initial and boundary conditions between the studies.

3.5 Applying ZFP Concept in Irrigation Systems

We believe that monitoring the ZFP could be relatively innovative to avoid salt accumulation in the root zone. Irrigation systems need prospective techniques that could help to manage and control successful irrigation disciplines. The ZFP movement with periodical water supply can be utilized to design an irrigation scheme that takes into consideration the relation between water supply rate and water movement in the soil.

This scheme could be useful to save irrigation water and to protect soil partially from soil salinity. It is important to determine the location of the ZFP as the redistribution of soil water could affect salt accumulation in the soil. In our case, all soil water starts to move upward after ZFP reached 30 cm depth. Therefore, if the ground water level is relatively near the soil surface and salt layer is above ZFP depth, it may accumulate to the surface creating several problems. In such cases, it is important to design irrigation scheme such that the period of water supply is short enough to keep ZFP at certain depth. In other words, water supply scheme should be designed in such a way to avoid ZFP disappearance.

4. CONCLUSION

For the first time the zero flux plane movement was successfully detected by both laboratory experiments and numerical simulations.

In the case of one time water supply, the experimental and the simulated results of the ZFP movement gave a reasonable agreement except for the soil surface when high temperature disturbed the water content profile.

In the case of the periodical water supply, the high water content of the deep zone is responsible for the ZFP disappearance.

The results suggest that ZFP method could be used to design powerful irrigation scheme in arid and semiarid areas and monitor and control partially the salt movement and accumulation associated with ZFP movement in the vadose zone.

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周期的水分供給に伴うゼロフラックス面の挙動

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要 旨

ゼロフラックス面(ZFP)とは、浅い領域では蒸発に伴う水分の上方移動が、深い領域では水分の下方移動が、同時に起きている土壌において、水分の上方移動と下方移動を分ける、理論的にはフラックスがゼロとなる深さの平面である。本研究では、ZFPの挙動を調べるために、カラム実験と数値実験によるシミュレーションを行った。黒ボク土に一度だけ水を供給し、0.15 cm/dayの蒸発速度と自由排水を与えたところ、全水頭分布とZFPについて、カラム実験とシミュレーションの結果がほどよく適合した。立川ローム土に周期的水分供給を与えたところ、カラム実験とシミュレーションともに、水分供給時に地表にZFPが現れ、ZFPは時間とともに下方へ移動し、30 cmの深さに到達したときにZFPが消失した。ZFPの消失は、土壌深層部の初期水分量が高かったために起きたものであると考察された。

キーワード：周期的水分供給, ゼロフラックス面, 不飽和土, Hydrus-2D, 深層土壌